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STUDY ON THE SEISMIC PERFORMANCE OF REINFORCED CONCRETE COLUMNS SUBJECTED TO TORSIONAL MOMENT, BENDING MOMENT AND AXIAL FORCE

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SUMMARY

During seismic excitation RC elements in three- dimensional structures such as arch ribs and L shape bridge piers, torsional moments in addition to bending moments, shear and axial forces affect the member. Interaction curves among those three sectional forces to use in nonlinear time history analysis has not been clarified yet.
In this paper 9 test models with different bending and torsional moments, pitch of hoop lateral tie are tested by newly developed loading machine. The test model has 400*400 mm cross section and 1600 mm length. The axial forces are 10% of target compressive strength of concrete, i.e. 4 MPa. Pitch of hoop lateral tie is 30mm or 60mm. Type of loading are pure bending, pure torsion and combined loading of moment and torsion.
Load deformation relationship, strain of reinforcement, crack and strain of surface, distribution of curvature and unit angle of twist, energy absorption and equivalent damping ratios obtained by these loading test are shown in detail.

INTRODUCTION

RC members in three- dimensional structures such as arch ribs and L shape bridge piers in urban highway have been constructed in seismic regions. During seismic excitation, not only bending moments, shear and axial forces but also torsional moments affect these members. But effects of torsional moments in these structures have not been considered severely in seismic design.
Outline of some existing researches dealing with combined loading containing torsional moment in RC members are as follows. Suda and et al. [1)] conducted cyclic loading test under the combination of bending, shear, and torsion using 6-degree of freedom loading machine to clarify the effect of torsional loading on seismic performance of high strength RC hollow section pier. The models were made by main reinforcement with high tensile strength and designed to fail by bending - torsion not by shear - torsion. From test results they obtained some knowledge such that the member failed by compression before tensile failure of main reinforcement occur. Tsuchiya and et al [2)] obtained FEM result for RC cylinder with bending, shear, and cyclic torsion using constitutive equation which was proposed by authors, and they agree the test result.
As mentioned above, research considering the combination of loads including torsional load are few, there-

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fore knowledge of characteristics of hysteresis loop of RC members with combination loads is lack, so there is a big difficulty to conduct the nonlinear time history analysis.
This paper presents test results of 9 models with two cases of pitch of hoop lateral tie subjected to different ratios of bending and torsional moments by newly developed loading machine. Experimental results for pure torsion have already been reported in Refs. 3) and 4)

EXPERIMENTAL METHOD

Test models

The model has 400*400 mm cross section and 1600 mm length for test, and footings at top and base ends to avoid local failure of column. Main reinforcements were anchored in footings using right angle hooks, therefore the pulling out of main reinforcement at the connection of column and footing was not observed. Figure 1 shows the sketch of the test model.

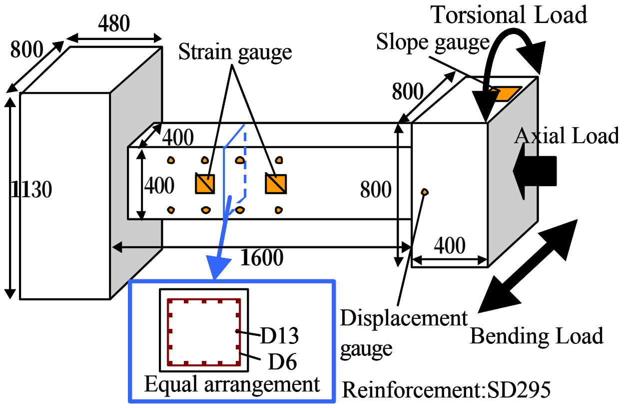


Figure 1 Sketch of the model(unit:mm)

Test cases

The axial force was 10% of target compressive strength of concrete, i.e. 4 MPa. Pitch of hoop lateral tie was 30mm or 60mm. Types of loading were bending / shear, pure torsion and combined loading of moment and torsion. Bending loads and torsional loads were cyclic loadings, but axial forces were maintained to be constant during test.
Table 1 shows test cases. Target loading ratio means ratio of incremental torsional moments and bending moments in interaction curve. The angle in parenthesis shows the direction for loading in interaction curve

Table 1 Test cases

No.	Initial axial stress		Target loading ratio (⊿Mt/⊿Mb)	Target strength	Pitch of hoop lateral tie
1	4Mpa	10%	～ (Pure Torsion)	40 N/mm^2	30mm
2	4Mpa	10%	1.73 (60°)	40 N/mm^2	30mm
3	4Mpa	10%	0.58 (30°)	40 N/mm^2	30mm
4	4Mpa	10%	～ (Bending / Shear)	40 N/mm^2	30mm
5	4Mpa	10%	～ (Pure Torsion)	40 N/mm^2	60mm
6	4Mpa	10%	1.73 (60°)	40 N/mm^2	60mm
7	4Mpa	10%	1.00 (45°)	40 N/mm^2	60mm
8	4Mpa	10%	0.58 (30°)	40 N/mm^2	60mm
9	4Mpa	10%	～ (Bending / Shear)	40 N/mm^2	60mm

Material test

Tables 2 and 3 show strength - test results of used material for model construction. Target strength of concrete was 40 MPa. SD295 was used for main reinforcement and hoop lateral tie.

Table 2 Test results of concrete

	Age	Compressive strength	Tensile strength	Elastic modulus
	(day)	(N/mm^2)	(N/mm^2)	(kN/mm^2)
No. 1	11	35.3	4.1	23.9
No. 2	32	49.3	3.4	30.1
No. 3	49	47.5	3.7	31.6
No. 4	6	40.6	2.9	24.6
No. 5	15	45.7	4.2	27.3
No. 6	38	60.4	4.8	36.6
No. 7	27	35.2	3.4	30.0
No. 8	37	51.6	3.8	31.0
No. 9	6	41.1	3.3	26.2

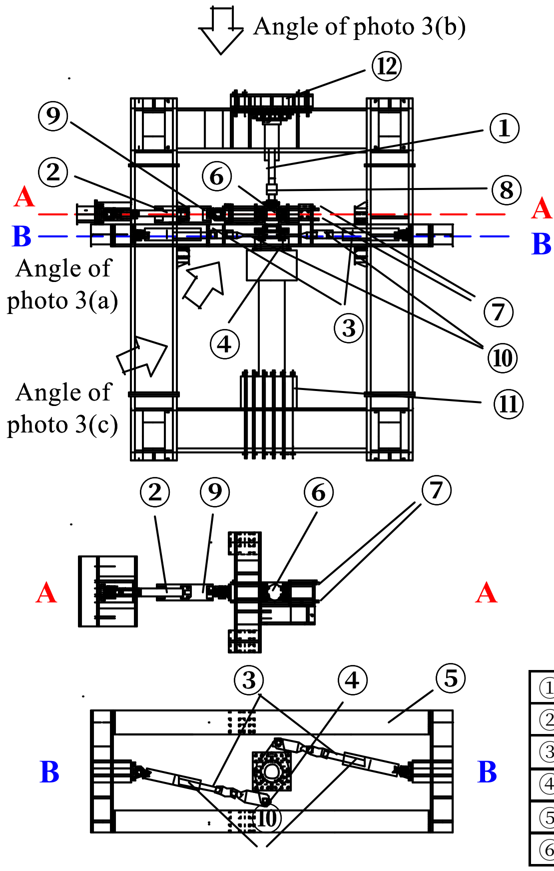
Loading machine

Figure 2 shows the sketch of loading machine. Axial loading was subjected by jack for axial loading (1) by way of (6) and (4). The number in parenthesis shows the equipment number illustrated in Figure 2. (6) can slide in axial direction in a case of shaft, so the constant axial force could be kept corresponding to the variation of model height. Furthermore when the bending deflection (lateral displacement) occurred, axial load was kept in the same direction by the existence of equipments (12) and (6).
Torsional loading was produced on the (4) due to two jacks (3) with the same pressure by way of an oil pump.
The bending loading was subjected to the model head by pushing or pulling the torsional loading frame in

which equipments (3) , (4) and (6) were mounted. Therefore bending loading was subjected independently to torsional loading.
Figure 3 (a) and (b) show the location of each jack, and Figure 3(c) shows the model subjected to torsional loading.

Table 3 Test results of steel bars

	Yield point (N/mm^2)	Yield strain ε_y ($\times 10^{-6}$)	Tensile strength (N/mm^2)	Elastic modulus (kN/mm^2)
D6	322	1823	497	169
D13	340	1885	489	174



①	Jack for Axial Load	⑦	PC rod
②	Jack for Bending Load	⑧	Load cell for Axial Load
③	Jack for Torsional Load	⑨	Load cell for Bending Load
④	Pedestal fixing model head	⑩	Load cell for Torsional Load
⑤	Frame for Torsional Loading	⑪	PC rod for anchoring of footing
⑥	Bearing for Pedestal	⑫	Slide for Axial Load Jack

Figure 2 Loading machine

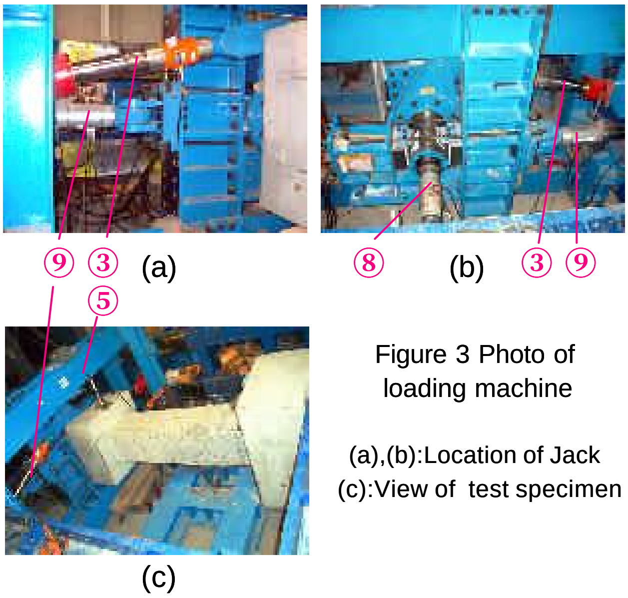


Figure 3 Photo of loading machine

(a),(b):Location of Jack
(c):View of test specimen

Loading procedure

Loading up to yield of reinforcement was subjected by holding the target-loading ratio to be constant in each loading step. After the yield the cyclic loading was subjected step-by-step using the integer times of yield displacements.
About the increment of loading, in case of increment of torsional loading is greater than that of bending loading, i.e. target loading ratio shown in Table 1 is greater than one, we call it torsional load surpass type. When increment of bending loading is greater than that of torsional loading, i.e. target loading ratio is smaller than one, we call it bending load surpass type. Neutral load type is named for target loading ratio equals one.
For example the loading image of torsional load surpass type is illustrated in Figure 4.

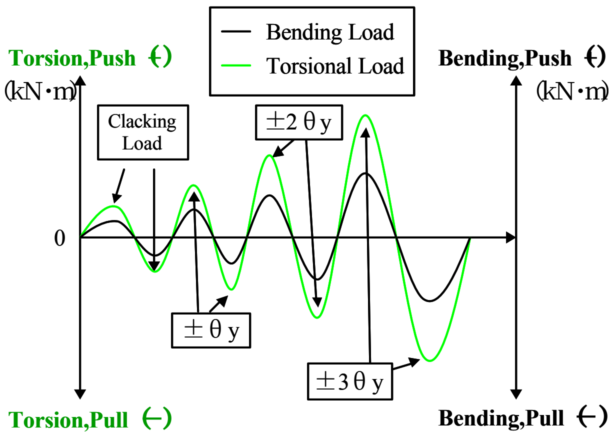


Figure 4 Image of loading in case of torsional load surpass type

Items of measurement

Axial, bending, and torsional loads were measured by load cells connected to each jack. Axial load was confirmed to have been constant during cyclic loading. Torsional moment was calculated by the following equation, in which P_E and P_w are values of load cells, l is the distance between the center of twist and connecting point of jack, and θ is the angle between the straight line of length l and the straight line perpendicular to jack axis(refer to Figure 5).

$$M_t = (P_E + P_W) \times l \times \cos\theta$$

The arrangement of displacement gauges, slope gauges and strain gauges for reinforcement and hoop lateral tie are shown in Figure 6. The displacement gauges was set by two rows in the same cross section, so twist angle was obtained by these two values. The value of displacement gauge No.9 was used as bending displacement of model.

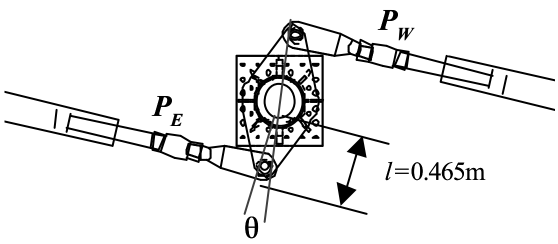


Figure 5 How to subject the torsinal load

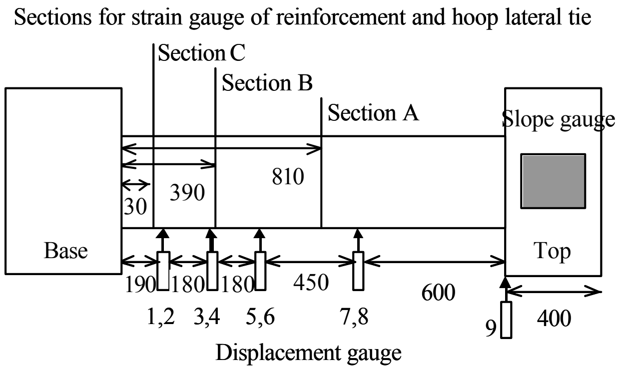


Figure 6 Location of gauges(plan view, unit:mm)

TEST RESULTS

Load deformation relationship

Models with the pitch of hoop lateral tie (ctc) = 30mm (No. 1- 4)

Figures 7 to 10 show torsional load - angle of twist and bending load - bending deflection relations for torsion load surpass type and bending load surpass type respectively. In these figures torsional load - angle of twist relation of pure torsion model (No.1) and bending load- bending deflection relation of bending / shear model(No.4) are also plotted. The hysteresis loop for surpass loading is almost same compared to pure loading type, but rigidity for un-surpass loading become small.

Models with the pitch of hoop lateral tie (ctc) = 60mm (No. 5- 9)

Figures 11 to 16 show the same relations for the models with ctc= 60mm. The skelton of torsional load - twist angle is different for the models with ctc= 30mm, and is more sensitive to pitch of hoop lateral tie than the skelton of bending loading - bending deflections. Neutral type shows the slight decrease of maximum loads but maintain similar configurations in both hysteresis loops.

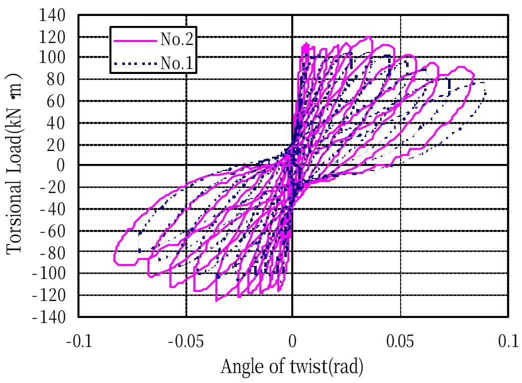


Figure 7 Torsional load - angle of twist relation
(torsional load surpass type:No.2,ctc30)

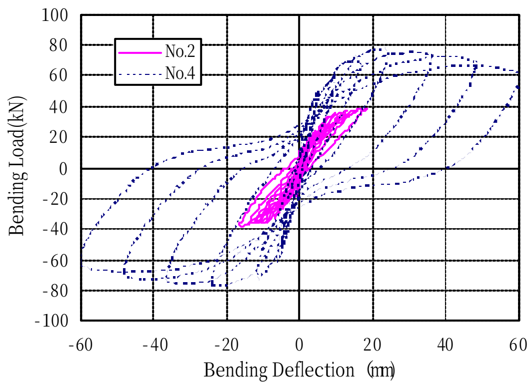


Figure 8 Bending load - bending deflection relation
(torsional load surpass type:No.2,ctc30)

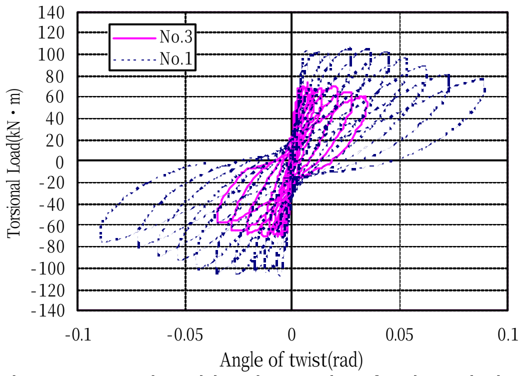


Figure 9 Torsional load - angle of twist relation
(bending load surpass type:No.3,ctc30)

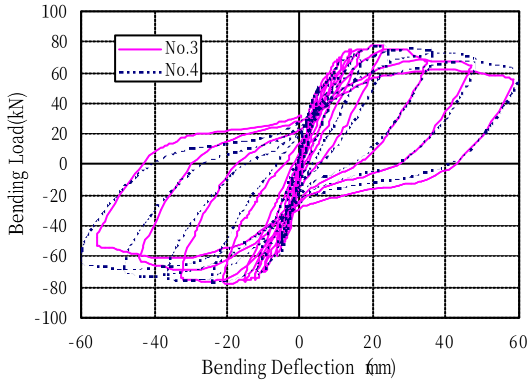


Figure 10 Bending load- bending deflection relation
(bending load surpass type:No.3,ctc30)

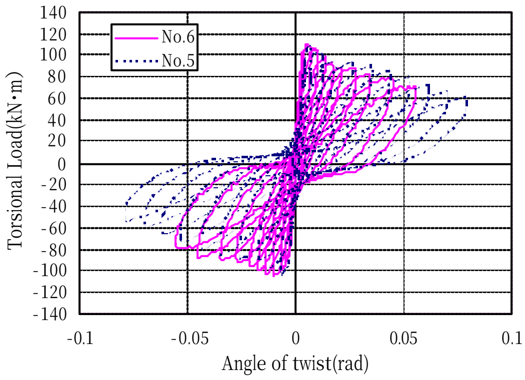


Figure 11 Torsional load - angle of twist relation
(torsional load surpass type:No.6,ctc60)

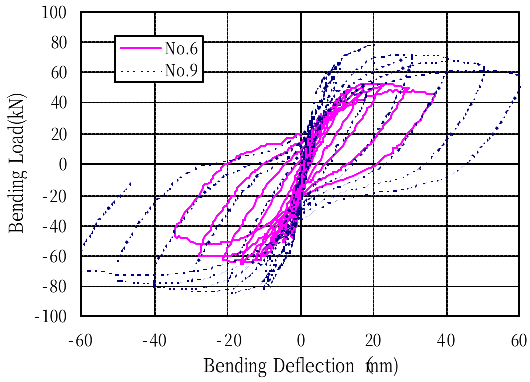


Figure 12 Bending load - bending beflection relation
(torsional load surpass type:No.6,ctc60)

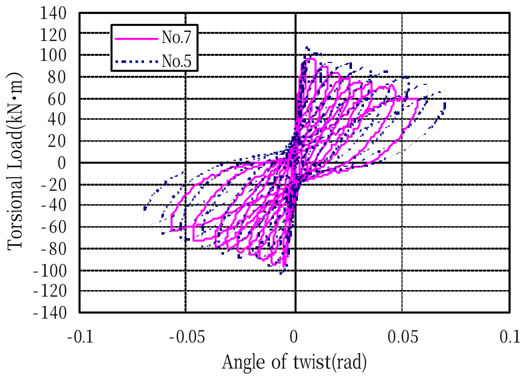


Figure 13 Torsional load - angle of twist relation
(neutral type:No.7,ctc60)

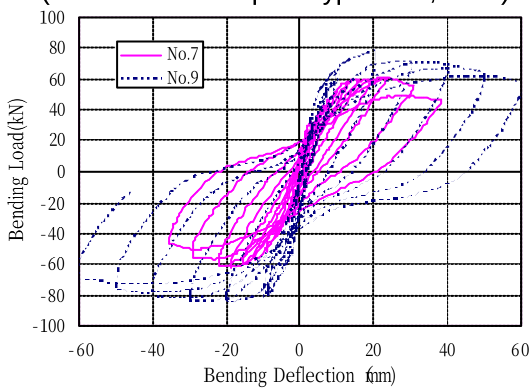


Figure 14 Bending load - bending deflection relation
(neutral type:No.7,ctc60)

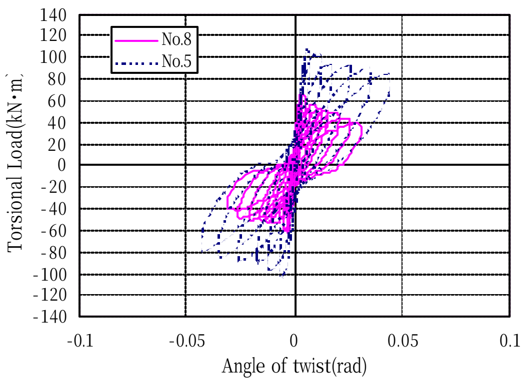


Figure 15 Torsional load - angle of twist relation
(bending load surpass type:No.8,ctc60)

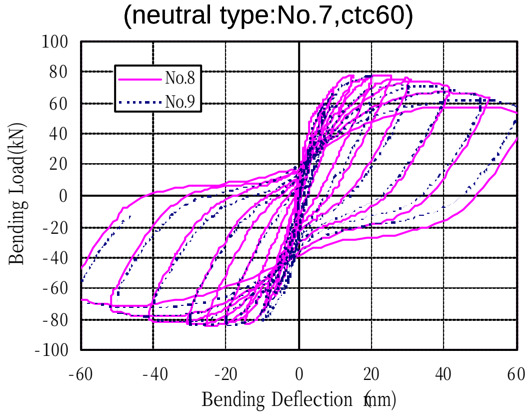


Figure 16 Bending load - bending deflection relation
(bending Load surpass type:No.8,ctc60)

Strain of reinforcement

Figures 17-20 show strain - angle of twist or bending deflection relations. In each figure, left draws show the strain of main reinforcement and right draws show the strain of hoop lateral tie. Strains are measured in mid section of the model. Tensile strain in hoop lateral tie uniformly increase due to expansion of cross section in torsional load surpass type, but do not increase in bending load surpass type.

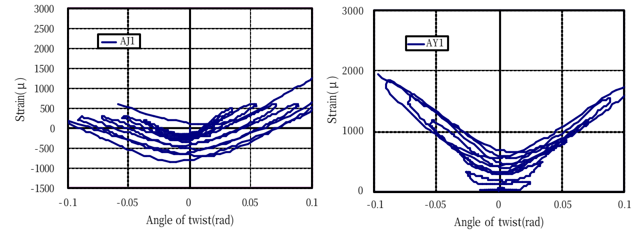


Figure 17 Strain - angle of twist relation
(pure torsion:No.1)

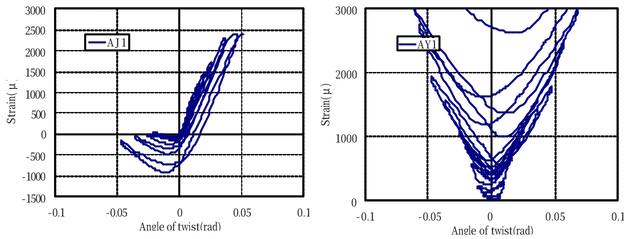


Figure 18 Strain - angle of twist relation
(torsional load surpass type:No.2)

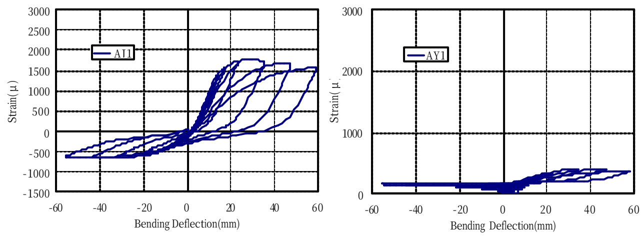


Figure 19 Strain - bending deflection relation
(bending load surpass type:No.3)

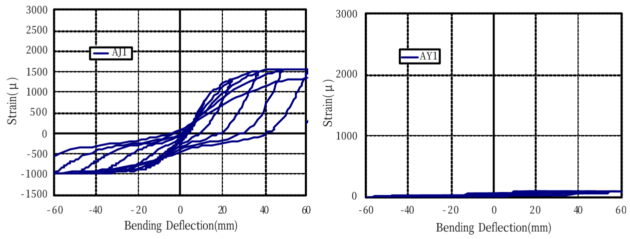


Figure 20 Strain - bending deflection relation(bending / shear:No.4)

Crack and strain of surface

Figures 21-26 show crack, strain, and principal stress direction in torsional load surpass type (No.2) and bending load surpass type(No.3). Strain and principal stress direction shown in Figures 23 to 26 correspond to crack drawing shown in Figures 21 and 22 respectively.

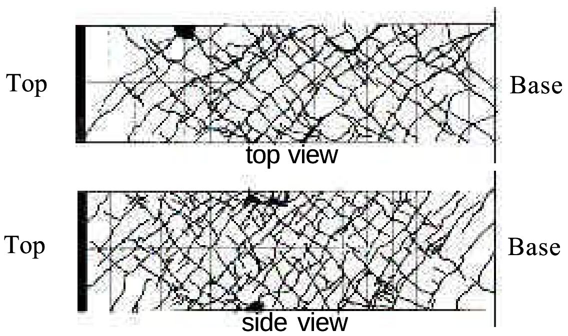


Figure 21 Cracking drawing
(torsional load surpass type:No.2)

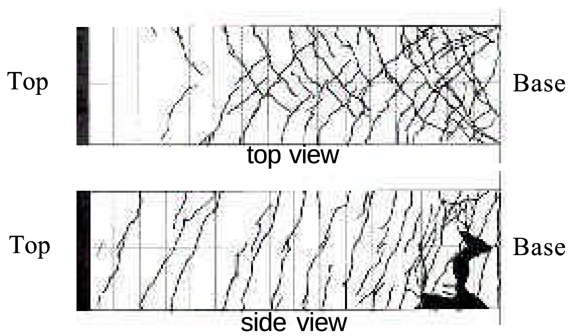


Figure 22 Cracking drawing
(bending load surpass type:No.3)

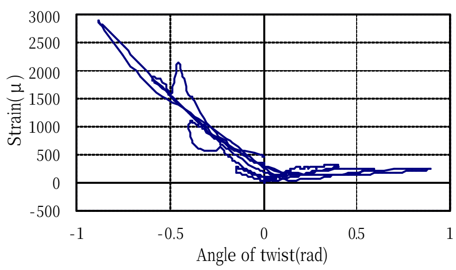


Figure 23 Strain - angle of twist relation
(torsional load surpass type:No.2)

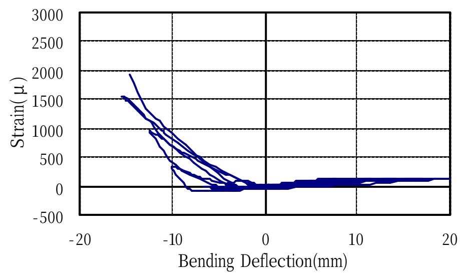


Figure 24 Strain - bending deflection relation
(bending load surpass type:No.3)

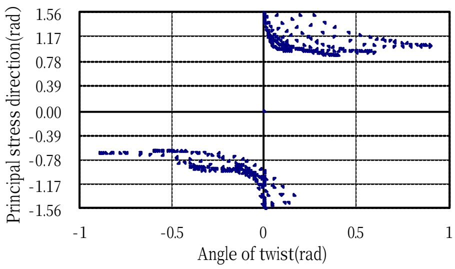


Figure 25 Principal stress direction - angle of twist relation(torsional load surpass type:No.2)

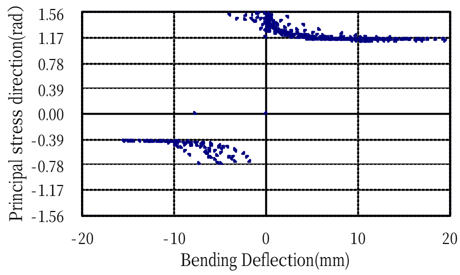


Figure 26 Principal stress direction - bending deflection relation(bending load surpass type:No.3)

Distribution of curvature and unit angle of twist

Figures 27 to 31 show the distribution of curvature and unit angle of twist in longitudinal direction. Location of plot is determined by the arrangement of displacement gauges. The values are obtained at the time of each event. Events are defined by surpass loading, i.e. crack, yielding, maximum load, and 80% of maximum load. In case of No.2 and No.3 (ctc=30mm) unit angle of twist at mid span is large in torsional load surpass type, but curvature at about 400mm from base is large in bending load surpass type. These are confirmed by the crack drawing. The unit angle of twist at base in bending load surpass type is large because of the development of plastic hinge by bending. In case of No.6 (ctc=60mm) unit angle of twist at mid span does not become large even in torsional load surpass type, because the maximum torsional load is relatively small.

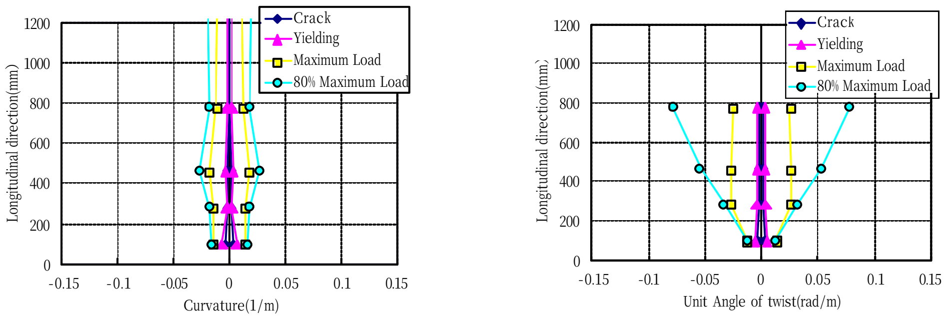


Figure 27 Curvature / unit angle of twist - longitudinal distribution (torsional load surpass type:No.2)

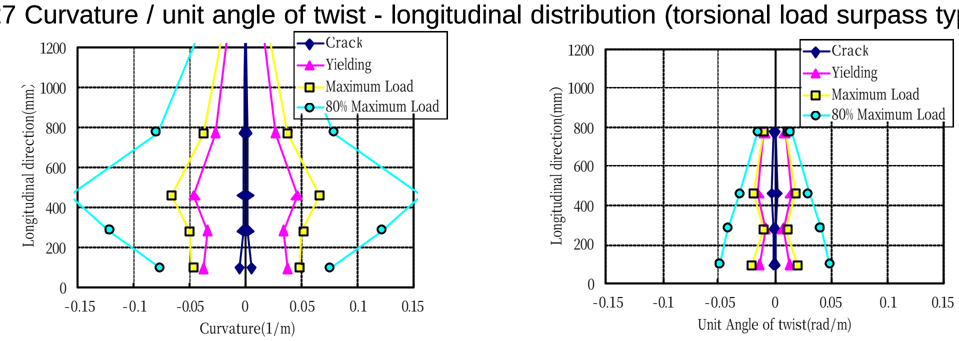


Figure 28 Curvature / unit angle of twist - longitudinal distribution (bending load surpass type:No.3)

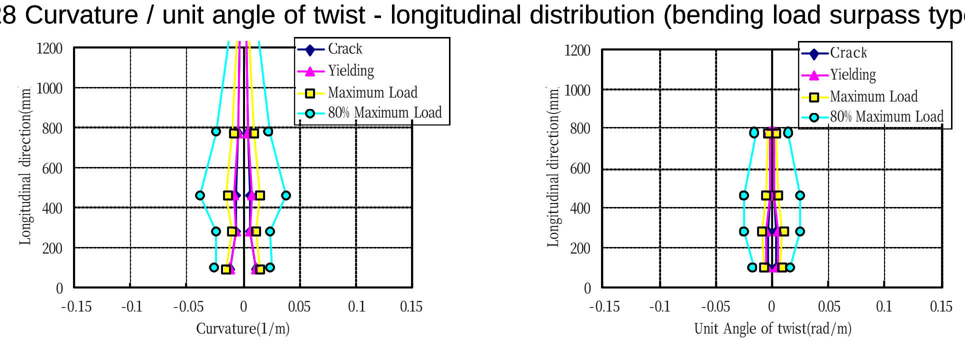


Figure 29 Curvature / unit angle of twist - longitudinal distribution (torsional load surpass type:No.6)

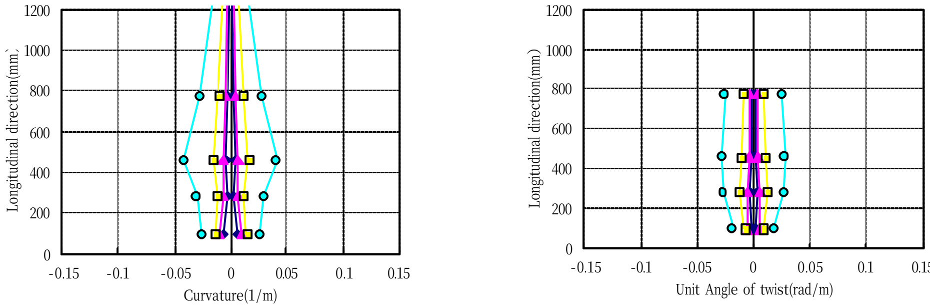


Figure 30 Curvature / unit angle of twist - longitudinal distribution (neutral type:No.7)

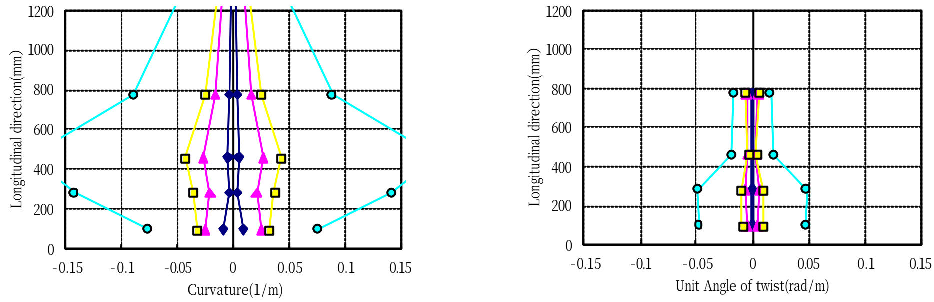


Figure 31 Curvature / unit angle of twist - longitudinal distribution(bending load surpass type:No.8)

Energy absorption and equivalent damping ratios

Figures 32 to 35 show the amount of energy absorption in each loading cycle. Plot with parenthesis is obtained by torsion or bending load only. In case of No.2 and 3 (ctc=30mm) amount of energy absorption for combined loading case is largest, but in case of No.6 and No.8 (ctc=60mm) amount of energy absorption is not largest in combined loading case.

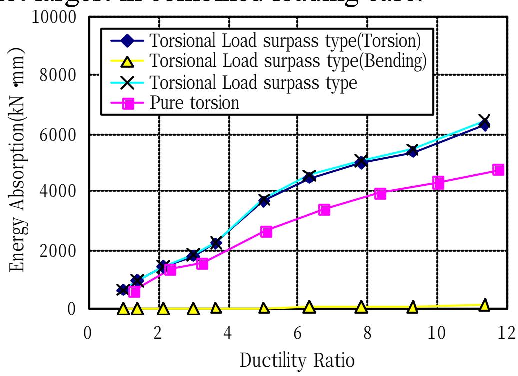


Figure 32 Amount of energy absorption (torsional load surpass type:No.2)

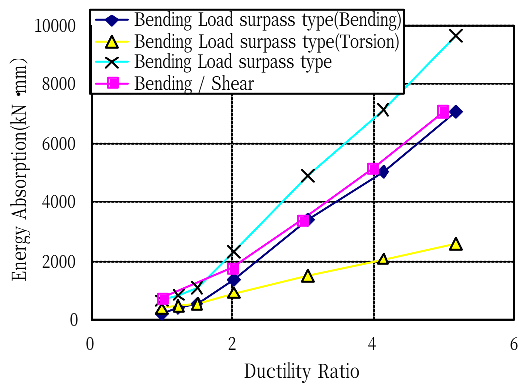


Figure 33 Amount of energy absorption (bending load surpass type:No.3)

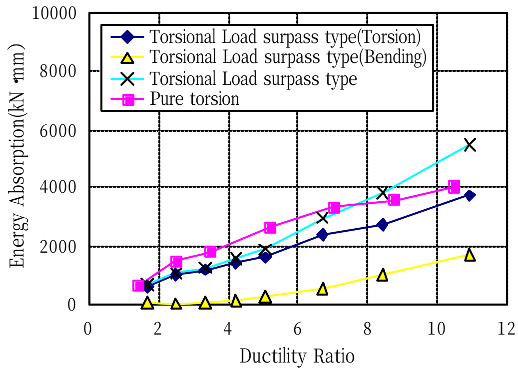


Figure 34 Amount of energy absorption (torsional load surpass type:No.6)

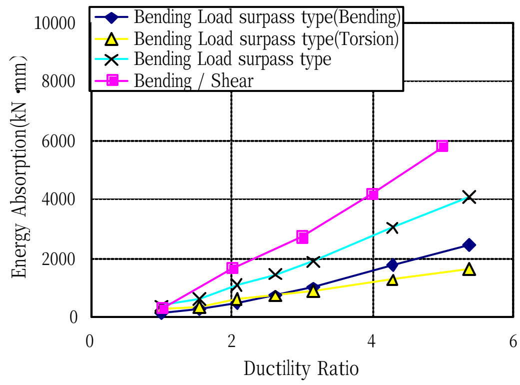


Figure 35 Amount of energy absorption (bending load surpass type:No.8)

Equivalent damping ratios are shown in Figures 36 to 39. In torsional load surpass type equivalent damping ratios do not change except for bending hysteresis in No.6, but in bending load surpass type damping ratios increase according to the ductility ratios.

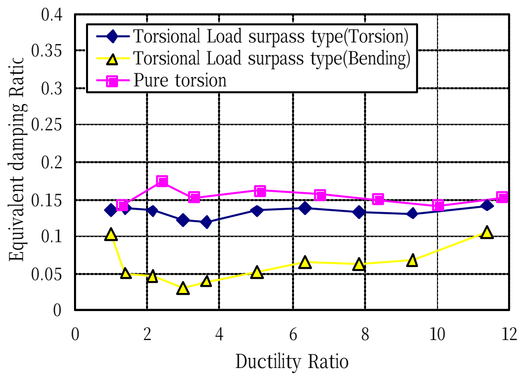


Figure 36 Equivalent damping ratio (torsional load surpass type:No.2)

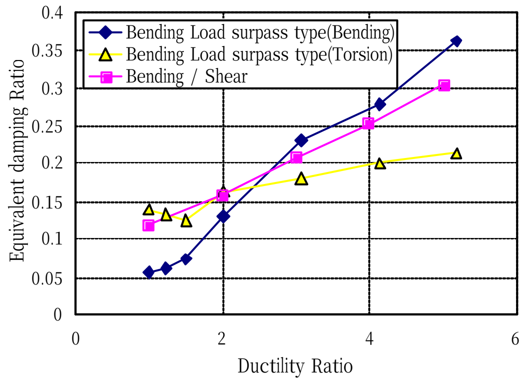


Figure 37 Equivalent damping ratio (bending load surpass type:No.3)

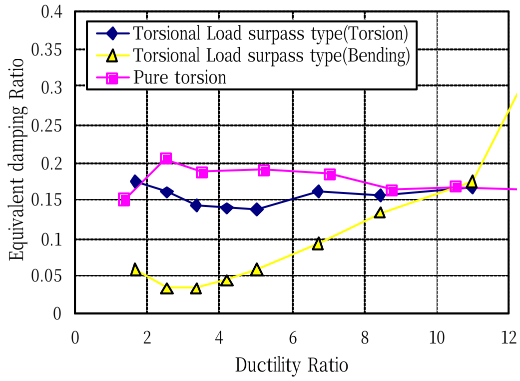


Figure 38 Equivalent damping ratio (torsional load surpass type:No.6)

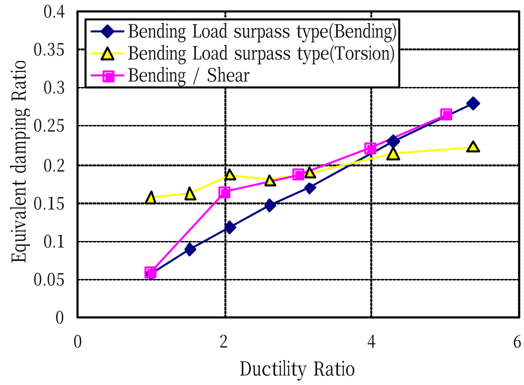


Figure 39 Equivalent damping ratio (bending load surpass type:No.8)

CONCLUSION

From test results conducted for models with hoop lateral tie of 30mm or 60mm pitch, and subjected to pure torsion, bending / shear and combined loadings, the following knowledge was obtained.

1) The pitch of hoop lateral tie remarkably affect for hysteresis loop of torsion, but not for bending.
2) For the model with poor hoop lateral tie (ctc=60mm), energy absorption is also carried out by bending in torsional load surpass type, but for the model with sufficient hoop lateral tie (ctc=30mm) energy absorption is not carried out by bending.
3) In hoop lateral tie, tensile strain uniformly increase due to expansion of cross section in torsion surpass type, but do not increase in bending surpass type.
4) In bending load surpass type, the unit angle of twist at base is larger than that at center, because of the development of plastic hinge by bending load.
5) In case of sufficient hoop lateral tie, amount of energy absorption for combined loading type is largest, but in case of poor hoop lateral tie largest energy absorption member vary in accordance with surpass loading.
6) Equivalent damping ratios increase according to the ductility ratios in bending load surpass type, but almost do not change in torsional load surpass type except for bending hysteresis of poor hoop lateral tie.

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